STUDIES FOR STUDENTS

THE STRUCTURE OF METEORITES. I.

THOSE portions of cosmic matter which from time to time fall to the earth and which are known under the general name of meteorites, have now for about a century been objects of collection and study. Earlier studies of this matter were, on account of its limited quantity and variety, necessarily confined chiefly to the description of individual masses. Comparative study, has, therefore, been carried on to only a small extent and the possible knowledge to be gained by investigation along this line is as yet far from complete. The number of localities from which meteorites are now known may be stated in round numbers as 550 and the total weight of cosmic matter now preserved and in one way or another available for study, as about 161 tons (146,716 kilograms).

Lines of investigation.—The lines along which the study of meteorites has been and is being conducted can be classified as follows, each, of course, being more or less intimately related to or inclusive of the other: (*a*) chemical, (*b*) mineralogical, (*c*) petrological, (*d*) physical, and (*e*) structural. Each of these may be (1) analytical, and (2) synthetical, and may include (3) the study of terrestrial analogies. Of the above courses of investigation the first three have been the lines along which study has been most extensively conducted hitherto. Summarizing briefly their results, it may be stated that the chemical investigation of meteorites has resulted in the identification of twenty-five elements, all similar to those known upon the earth; the mineralogical in the determination of at least twenty mineral species, some of which are similar and others dissimilar to terrestrial compounds, and the petrological in the classification and tabulation of the characters which meteorites display as mineral aggregates.

The physical investigation of meteorites has been confined chiefly to studies of their spectra and comparisons of these with the spectra of comets, nebulæ, and other heavenly bodies. Studies of thermo-luminescence, magnetism and polarity as exhibited by meteorites have also been made. With the results of the structural studies of meteorites it is the purpose of the present paper to deal in some detail.

Structure a feature distinguishing meteorites from terrestrial rocks.—It is from the point of view of structure that meteorites differ most completely from terrestrial rocks. In chemical, mineralogical, petrological and physical characters some meteorites closely resemble terrestrial rocks. The meteorite of Juvinas, for instance, so far as the above characters are concerned, is similar to a basalt, while many of the iron meteorites find a perfect analogue in the terrestrial irons of Greenland. When the structure of meteorites is considered, however, a distinction is apparent. No resemblance to the clastic texture of the Juvinas meteorite is to be found among terrestrial basalts, nor does the terrestrial nickel-iron show satisfactorily the Widmanstätten figures so characteristic of the iron meteorites.

It is along this line of study that the geologist finds problems which his science is especially adapted to solve, for the problems afforded are similar in many respects to those included under the group of structural and dynamical, or, as it is sometimes termed, phenomenal geology. Just as studies of the latter sort avail to give a knowledge of the forces and conditions under which different rock structures and rock movements are produced, so studies of the structure of meteorites may be expected to discover the conditions under which cosmic matter is formed and the forces to whose action it is subject in space. Since, further, this cosmic matter reaching us as meteorites has striking and important analogies with that, not alone of the crust of the earth, but it may be believed also of its entire substance, the fascinating possibility is presented of reading in the mass of meteorites many chapters in the history of the earth which would otherwise be locked up within its interior.

Matter of meteorites of two kinds.— Matter constituting meteorites may be described as of two kinds, metallic and stony. The metallic matter is chiefly an alloy of iron and nickel, the stony matter chiefly the silicates chrysolite, pyroxene, and feldspar. Single meteoric masses may consist of but one of these kinds of matter or may be made up of a union of the two.

Three groups of meteorites according to their components.— According to the relative quantities of each of the two above mentioned kinds of matter it is convenient to divide all meteorites into three great groups. Those made up wholly or largely of metal (*aerosiderites, holosiderites*) form the first group. Those made up of about equal quantities of metal and stone (*aerosiderolites, lithosiderites, syssiderites*) form the second group. Those made up wholly or largely of stone (*aerolites, sporadosiderites*) form the third group. No sharp dividing line can be drawn between these groups. They pass into one another by every gradation, and meteorites of the two kinds even occur in the same fall. Yet meteorites of these groups differ in many essential characters and their separation becomes a matter of great convenience in study. For purposes of the present study the three classes will be sufficiently designated by the terms iron meteorites, iron-stone meteorites, and stone meteorites.

Two groups of meteorites according to their origin. — With respect to their origin meteorites may be either (1) monogenic (of single origin) or (2) polygenic (of various origin). Most of the iron meteorites are plainly monogenic. Many show such homogeneity and uniformity of structure as could belong only to a single crystal. Thus the iron meteorite of La Caille, a mass of 591 kilos in weight, contains inclusions of troilite arranged in parallel rows throughout in such a manner as to indicate a uniform and continuous crystallization of the entire mass. Likewise from a mass of a Toluca meteorite a cube may be cut which shows on etching a perfectly regular octahedral structure throughout. The same parallelism of planes may be traced on an etched section of almost any of the so-called cubic meteorites, such as Coahuila, Hex River, etc. A few iron meteorites

are however plainly polygenic. An etched section of the Mt. Joy meteorite for example shows the mass plainly to be made up of irregular iron fragments. The structure of each fragment as shown by its etching figures is *sui generis*, and indicates an independent origin. The iron of Zacatecas is likewise made up of individual grains the size of a hazelnut to that of a walnut. These are separated by areas of troilite.

Many of the iron-stone and stone meteorites are monogenic but more are made up of two or more different kinds of rock. To draw the dividing line between the monogenic and polygenic meteorites of the last two classes is not an easy task and the opinion of no two observers would probably be the same in regard to it. The meteorite of Stannern for instance was described by one observer as crystalline and by another as clastic. Tschermak, who has given the matter profound study, is disposed to regard practically all stone meteorites as of a tuffaceous or clastic character while Wadsworth after examining many meteorites concluded that none which he had examined could be considered "fragmental in the sense of consolidated cold masses joined together." The present writer can only state that in his opinion some stone meteorites are so uniform in character that crystallization from a single magma is indicated while on the other hand many meteorites have a clearly brecciated and tuffaceous character showing them to be polygenic.

Structures of terrestrial origin to be eliminated.—In all study of the structure of meteorites with a view to learning their preterrestrial history, care should be taken to eliminate all phenomena of terrestrial origin. Thus the crust of meteorites and their surface markings are usually considered, and without doubt properly, to be produced during the passage of the mass through the earth's atmosphere. The possible effects on the interior of a meteoric mass, of heat developed by such passage should also be borne in mind in study. Again the force of impact with which a meteorite strikes the earth is often very great. It should be considered whether such a blow might not give rise to phenomena of internal movement within the mass. Again

processes of corrosion and decomposition go on if the meteorite is exposed on the earth's surface for any length of time, which may have their effect on the structure of the meteorite. These therefore must be judged and eliminated. Again, the fissures found in meteorites are believed by many to be the result of cracking from the sudden development of heat caused by the entry of the mass into the earth's atmosphere and the veins of meteorites are by some thought to be fissures filled by matter fused by such heating. Due weight must be given these possible effects and all that are certainly of terrestrial origin must be left out of consideration.

Uniformity of mass structure of single meteorites.—The iron meteorites usually show remarkable uniformity of structure throughout. Sections from different portions of a single mass or even different masses of the same fall usually give on etching, figures so similar that the meteorite to which they belonged can be recognized at a glance, even if the specimens have been widely separated. In some, however, there are variations in the same mass. Thus the Floyd county iron according to Kunz and Weinschenk while possessing a generally cubic structure shows portions which are granular; the Linnville iron according to Kunz is partly of cubic structure and partly amorphous. The Carlton iron is partly rich in plessite and partly poor in plessite. The Holland Store iron has portions coarse-grained and fine grained. Four of the five masses found near Staunton, Virginia, are quite similar in structure, showing on etching, figures made up of short, swollen bands. The etching figures of the fifth mass are, however, made up of long, straight bands. Moreover the taenite of the first four is brittle, of the fifth elastic. So sharply does the latter mass differ from the others that Brezina regards it as belonging to a different fall, but it is more likely that the differences are those of structure. Such exceptions are however so rare as to emphasize the fact that on the whole iron meteorites are uniform in structure. Speaking in a general way the iron-stone and stone meteorites are likewise uniform in mass characters although such as are

clastic or brecciated have the variations which might be expected from the accidents of aggregation. The monogenic meteorites may show variations from fine grain to coarse grain and vice versa and some portions may contain more stone or metal than others, but the general structure may be said to be uniform.

Similarities of structure in meteorites of different falls.—While the individuals of a single fall are usually similar in structure and composition those of different falls often differ so that they may be easily distinguished. In comparing the meteorites of a large number of falls, however, similarities are readily seen which permit the grouping of several falls together as being of practically identical matter. A number of classifications of this sort have been made of which those of Brezina and Meunier are the latest and most complete. Brezina, who makes structure the leading feature of his classification, has thus reduced all known meteorites to sixty-one groups, while Meunier, with whom mineralogical composition is the chief criterion, makes sixty-two groups.

Degrees of coherence.—The iron meteorites are, as might be expected, usually strongly coherent and tenacious to a high degree of malleability. Yet there are variations in this respect. The iron meteorites showing coarse etching figures can usually be sawed only slowly and with great difficulty, while those of an amorphous or finely crystalline character cut more readily. Some iron meteorites, such as those of Coahuila and Nelson county, can be broken readily by the blow of a hammer. Among the stony meteorites all stages of consolidation may be traced from those of an almost flint-like toughness (Long Island) to those so friable as to crumble on handling (Warrenton). The majority of stony meteorites are fairly coherent so as to take a good polish.

Kinds of structure according to texture.— According to what is often known as rock texture, meteorites display a number of variations which are for the most part entirely comparable with similar variations seen in terrestrial rocks and may be described by the same terms. Accordingly, among the monogenic meteorites

crystalline, cryptocrystalline and vitreous or amorphous structures may be noted. Among the polygenic meteorites, brecciated, agglomerated, psammitic or sandstone-like and tuffaceous structures may be noted. Stratified, foliated, and fibrous structures are entirely lacking. Both among monogenic and polygenic meteorites occurs a kind of structure resulting from the mass

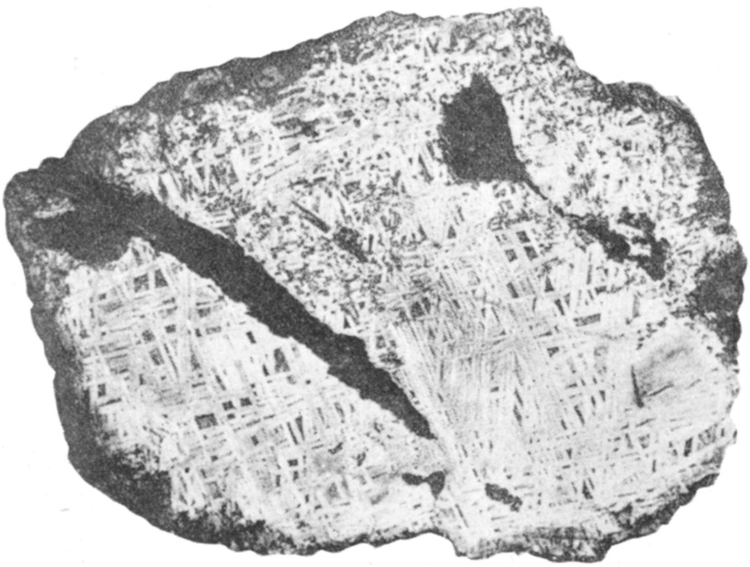

FIG. 1.—Widmanstätten figures. Meteorite from Toluco, Mexico.

being made up largely of little spheres called chondri. The structure of such meteorites is not strictly comparable to that found in any terrestrial rocks. Meunier describes it by the term oölitic, but the analogy is not a very close one. The structure, therefore, requires a distinctive term, chondritic, meaning a rock made up wholly or largely of chondri.

CRYSTALLINE STRUCTURE.

Iron meteorites.—Sections of most iron meteorites when heated or etched by acids or other etching agent display upon their surface well-marked figures formed of series of parallel bands intersecting in two or more directions. These figures

are called, after Alois von Widmanstätten, who first produced them in the year 1808 by heating a section of the Agram meteorite, Widmanstätten figures. The production of these figures is evidence that the meteorites on which they occur (1) have a well-defined crystalline structure and (2) are not homogeneous in composition. Evidence of crystalline structure is not confined to results obtained by etching: many meteorites show in their natural condition a structure of plates intersecting at definite angles. Study of the angles at which the bands meet both in etched and natural specimens shows that the crystallization of moſt iron meteorites is octahedral, *i. e.*, they are formed of plates or lamellæ arranged parallel to the four pairs of faces of the octahedron.

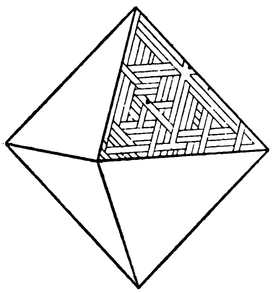
FIG. 2.

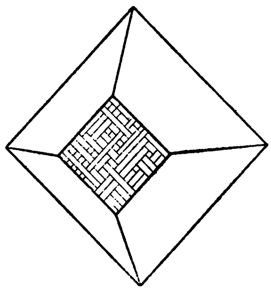
FIG. 3.

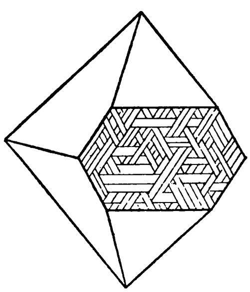
FIG. 4

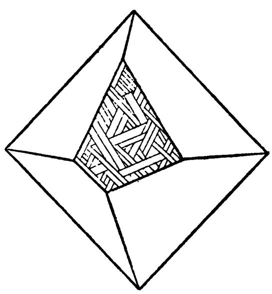
FIG. 5.

Though this arrangement may for practical purposes be considered a simple one, it is really according to Linck the result of a polysynthetic twinning. The angles at which the bands intersect in any given section depend wholly on the direction of the section, as the accompanying figures will show. If the section is parallel to an octahedral face it will show three systems of bands intersecting at angles of 60° (Fig. 2). If the section is parallel to the face of a cube there will be two systems of bands intersecting at angles of 90° (Fig. 3). If the section is parallel

to a dodecahedral face there will be two systems of bands intersecting at angles of 109° 28′ and two others parallel to each other which will bisect this angle (Fig. 4). Sections in any other direction (obviously by far the most common) will produce bands running in four directions and intersecting at unequal angles (Fig. 5). A small number of iron meteorites show a cubic rather than an octahedral crystallization, *i. e.*, they are formed of plates arranged parallel to the faces of a cube. These are known as "cubic irons," or hexahedrites. A still smaller number exhibit no crystalline structure nor Widmanstätten figures. These are known as amorphous irons or ataxites. The relative numbers of these kinds of irons given in Brezina's classification are, of the octahedral irons, 125; of the cubic irons, 26; and of the ataxites, 14. Among the octahedral irons the particular figures exhibited will vary slightly with almost every fall, on account of varying width, length, shape and arrangement of the bands and abundance and forms of included matter. Width of bands is made by Brezina the basis of classification of the octahedral irons. He describes the widths as varying from more than 2.5 ^{mm} to less than 0.1 ^{mm}. When the intimate structure of the bands themselves is considered, they will be found to consist of a broad band of dull luster and iron gray color depressed below the surface when etched or covered with a thick layer of oxide when heated, bounded on either side by thin lamellæ of bright luster and silver white to yellow color, which stand out in relief or are little oxidized. To the broadly banded alloy, Reichenbach, who first investigated this structure, gave the name of Balkeneisen or *kamacite*, from κάμαξ, a pole or shaft. To the narrow banded alloy he gave the name of Bandeisen or *taenite*, from ταινία, a fillet or ribbon. When angular interstices occur between the intersecting bands they are often filled with an alloy intermediate in properties between kamacite and taenite. To this Reichenbach gave the name of Fulleisen or *plessite*. The three alloys together he called "the triad." Chemical analysis of the members of the triad shows them to be alloys of nickel and iron, the first two of which have a fairly

uniform chemical composition, though not sufficiently constant to warrant their being considered distinct mineral species. The percentage of nickel is lowest in kamacite, thus accounting for its greater solubility in acid. The formula Fe_{14} Ni expresses the usual proportion of iron and nickel which it contains. Taenite contains a much larger proportion of nickel and hence is less soluble in acid. Its formula has been given both as Fe_6Ni and Fe_5Ni_2. According to Tschermak the taenite of the Ilimäe meteorite consists of a network of different substances, and it is doubtful whether in any meteorite it is a homogeneous substance. The third member of the triad, plessite, has a very variable composition and the latest investigations make it doubtful whether it differs essentially from kamacite. Inclusions of other minerals occurring in iron meteorites are usually surrounded by a layer of kamacite. Kamacite of this sort, while it does not differ in composition or structure from the ordinary kamacite, has been designated by Brezina as "*wickel-kamazit*" (swathing kamacite) and was called by Reichenbach "Hulleisen." While the octahedral irons always contain two or more of the above alloys, cubic irons contain only one, viz., kamacite. This usually shows a parallel banded structure on etching, but is not divided into well-marked lamellæ. Etched sections of cubic irons also exhibit fine depressed lines called Neumann lines. They are somewhat promiscuously scattered, having neither the abundance nor the regularity of Widmanstätten figures. They are usually interpreted as intercalated lamellæ in twinning relation to the main individual which are more easily dissolved by acid than the other lamellæ. They have been likened to the twinning lamellæ parallel to $-\frac{1}{2}R$ often seen on a piece of calcite. Tschermak regards their formation as simultaneous with the crystallization of the iron, while Sadebeck and Linck consider them of secondary origin, perhaps as a result of jar or shock. Many cubic irons also exhibit orientated sheen (*krystal damast, moiré metallique*). This is formed partly by differential etching

of parallel bands and partly also by the above described Neumann lines. Sheen, Neumann lines, and parallel banded structure of the cubic meteorites will be found on close examination to characterize the kamacite of many octahedral irons (*schraffirten kamazit* of Reichenbach), while the kamacite of other octahedral irons is wholly granular (*fleckig kamazit* of Brezina).

Regarding the part played by the different alloys in the process of crystallization, opinions differ, though the general opinion is that the kamacite crystallized first and the other substances arranged themselves accordingly. Sorby likened the process to the forming of needles of ice on the surface of water, leaving angular spaces which were filled later. J. Lawrence Smith on the other hand, thought that the foreign minerals, such as schreibersite, separated and crystallized first and the purer alloys followed. Huntington is of a similar opinion and draws attention to the close resemblance in appearance between Widmanstätten figures and the arrangement of inclusions of magnetite in mica in support of the view.

Most authorities agree that the crystalline structure exhibited indicates that the masses must have remained for a long time in a fused or viscous state from which they cooled but slowly. The conclusion of Tschermak was that "the greater number of meteoric irons exhibit a structure which indicates that each formed a part of a large mass possessing similar crystalline characters and the formation of such large masses presupposes long intervals of time for tranquil crystallization at a uniform temperature." Sorby reached a similar conclusion and regards the Widmanstätten figures "as the result of such a complete separation of the constituents and perfect crystallization as can occur only when the process takes place slowly and gradually. They appear to me to show that the mass was kept for a long time at a heat just below the point of fusion."

2. *Iron-stone meteorites.*—The metallic portions of most meteorites of this class show Widmanstätten figures on etching. The mineral silicates entering into the composition of the mass also often exhibit well-defined crystal forms, the perfection of which is

sufficient to permit accurate measurements of the crystal planes. A curious feature of these crystals, however, and one which has as yet received no adequate explanation is that they usually exhibit a rounding of the solid angles and edges, giving an appearance of a sphere on which facets have been cut.

3. *Stone meteorites.*—To what extent a primary crystalline structure characterizes stone meteorites, is a point regarding which, as has been said, no two observers are likely to agree. The minerals of many meteorites occur in well crystallized form, but whether they have crystallized *in situ* or are mere splinters from previously existing masses is a disputed point in most cases. The number of stone meteorites showing a holo-crystalline structure similar to that characterizing terrestrial rocks is certainly small. Such as may be of this character are fine-grained and resemble fine-grained basalts in their structure.

Among minerals occurring in well defined crystal forms, whatever their relation to the mass as a whole, enstatite, chrysolite, augite, and plagioclase are the most common and characteristic. The crystals of these minerals usually have well-defined boundaries and exhibit planes corresponding to those of terrestrial minerals of the same kinds. Twinned individuals are common and a lamellar arrangement of inclusions is sometimes seen. There is a complete absence, however, of layers of growth or of zonal structure so common in the minerals of volcanic terrestrial rocks. The crystal individuals often contain large quantities of glass and often present a highly fissile structure. Another remarkable feature is a complete absence of fluid inclusions. Gas pores while occasionally to be seen are exceedingly rare. The latter fact, it may be remarked, furnishes a strong argument against any theory which regards meteorites as having been formed directly from vapors.

CRYPTOCRYSTALLINE AND AMORPHOUS STRUCTURES

1. *Iron meteorites.*—The term amorphous irons or ataxites is usually used to designate iron meteorites which give no Widmanstätten figures on etching. Such irons are few in number and the

present supposed number will doubtless be further reduced by careful study since some accredited meteorites will be found to be artificial irons and others will give Widmanstätten figures on further treatment. The true ataxites resemble ordinary cast iron in structure. There are sometimes variations in a single mass from a compact homogeneous structure to one of a coarse grained character. Several show indistinct broad bands and others a sheen (*Eisenmohr, moiré metallique*) on etching. Inclusions of graphite, phosphides and sulphides of iron (such as schreibersite, troilite, etc.) occur as in the octahedral irons. Unusually high content of nickel characterizes some, while others have an average composition. On the whole the ataxites may be said to form an anomalous and little understood group.

2. *Stone meteorites.*—No stone meteorites are amorphous in structure as a whole; only the ground mass is sometimes found to be of this character. In some cases a ground mass appearing amorphous is found in reality to be made up of consolidated fragments of dust-like minuteness. In other cases, as in the stones of Richmond and Goalpara, the ground mass is really semi-glassy and unindividualized. The ground mass of most of the carbonaceous meteorites is of a black unindividualized character, and appears closely allied to the substance to be described later as forming veins. In the brecciated stones of Orvinio and Chantonnay a black ground mass cements the fragments of chondritic texture together and exhibits a distinct flow structure about them. A brown glass is also found cementing together some of the crystalline and tuffaceous meteorites.

BRECCIATED STRUCTURE.

This is of rather common occurrence. According to Wülfing's classification it characterizes meteorites of sixty-two falls. Breccias occur both of the type of angular fragments compressed together and of angular fragments imbedded in a ground mass which may have been at one time in a fused or pasty condition. Among the iron meteorites the fragments are largest in the Mt. Joy meteorite. The contour of each of these is so distinct that

there can be little doubt that the mass was made up by the aggregation of solid angular fragments. The meteorites of Zacatecas and Kendall counties have a similar structure, though the component fragments are much smaller.

Some of the iron-stone meteorites have likewise a brecciated structure resulting from the imbedding of angular masses of silicates in a metallic base. The meteorite of Copiapo, for example,

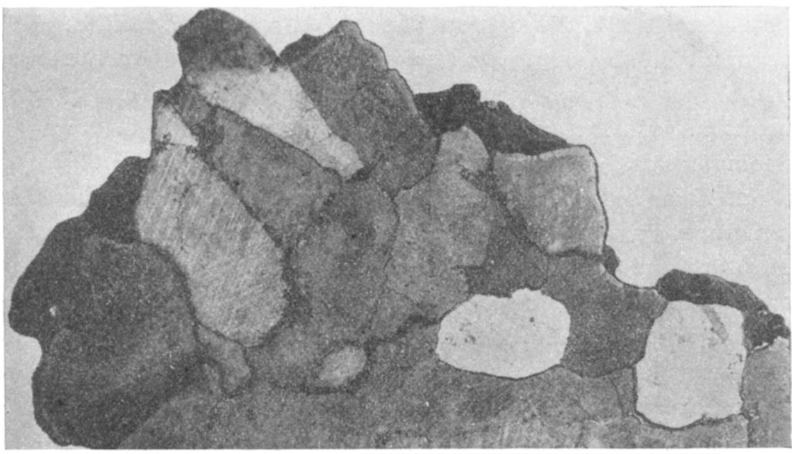

FIG. 6.—Brecciated structure. Mt. Joy Meteorite.

has such a structure and its formation is exactly analogous, in the view of Meunier, to the dike breccias produced on the earth by intrusive igneous eruptions tearing off fragments of the rock through which they have ascended and enclosing them in its pasty mass. In this case the intrusive matter was fused nickel-iron. In other iron-stone meteorites, such as Vaca Muerta and Eagle Station, the silicate fragments are likewise angular. Reichenbach is authority for the statement that the iron in these adapts itself to the form of the stone rather than the contrary.

The fragments forming the breccia in stone meteorites are often of considerable size. The largest which I have noted in the stony meteorites (Weston) is about one cubic inch in contents.

Often the fragments differ enough in color from one another, or from the ground mass, so that the brecciated character is plainly visible to the naked eye. In the stone of Weston, for example, the ground mass is gray, the enclosed fragments blue. In the stone of Siena the angular fragments are of a dark color and the enclosing magma is light colored, while of Bandong, Saint-Mesmin and others the reverse is true. In other meteorites the two components differ chiefly in grain and coherence, as in the meteorites of Jelica, Manbhoom, and Soko-Banja. In these the ground mass is of a somewhat coarse, friable character, while the enclosed fragments are of a dark, fine-grained rock. In regard to the ground mass of other brecciated stone meteorites it may be stated that it may itself be made up of rock splinters, *i. e.*, have a tuffaceous character, or it may be crystalline or half glassy. The half glassy ground mass of the Orvinio and Chantonnay meteorites, as already noted, shows a distinct flow structure around the fragments which it encloses.

AGGLOMERATED, SANDSTONE-LIKE AND TUFFACEOUS STRUCTURES.

These may be said to differ from brecciated structure only in the smaller size of the component fragments. The fragments may range from the size of small peas in meteorites of agglomerated structure through that of coarse sand in those which are sandstone-like to that of splinters and fine dust in the tuffaceous meteorites. In the agglomerated meteorites it is often possible to recognize different kinds of rocks. Thus in the Parnallee meteorite Meunier believes he has recognized seven distinct lithologic types. Of the sandstone-like meteorites that of Chassigny is the best example. It is made up of rounded grains of the size of coarse sand. The Shergotty and Ibbenbühren meteorites are likewise granular in appearance. Not all observers, however, agree that the above are clastic in their origin. The tuffaceous structure is a common one in meteorites, Tschermak, as already noted, regarding practically all stony meteorites as of this nature. The resemblance of these to terrestrial volcanic tuffs is very close, though the stratification which usually characterizes the latter has never been

observed. The tuffaceous meteorites are made up of splinters and dust varying in degree of consolidation. They are often finely porous so as to soak up fluids readily. The splinters of which they are made up may be similar in character (Shalka) or strikingly dissimilar (Luotolaks).

O. C. FARRINGTON.

(To be continued)